Cooling Design of Shielding at MOMENT

Jianfei Tong, Qingnian Xu,YuanYe,Binzhou, Tianjiao Liang

August 11, 2015

Insititue of High Energy Physics, CAS

CSNS
CHINESE ACADEMY OF SCIENCES

Outline

1. Introduction

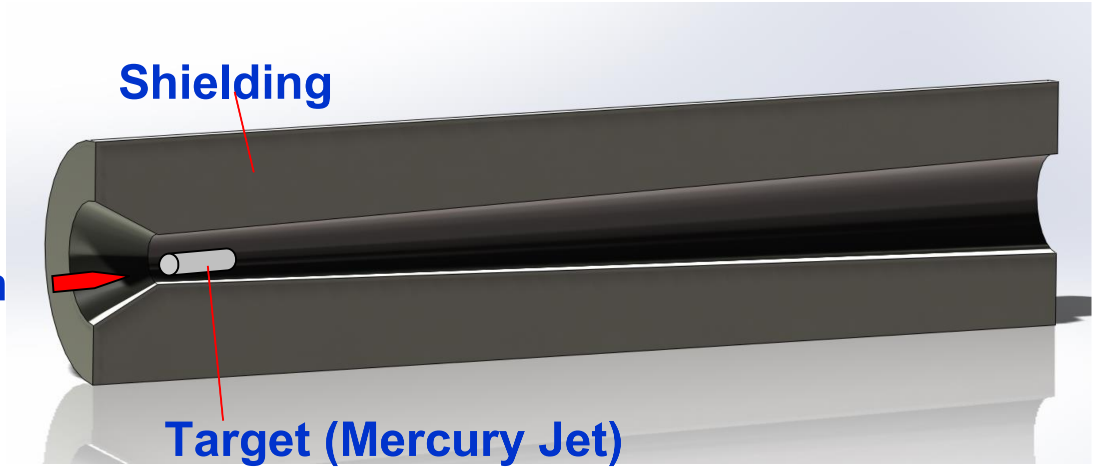
2. Heat Deposition Calculation

3. Cooling Structure Design & CFD Analysis

4. Conclusion

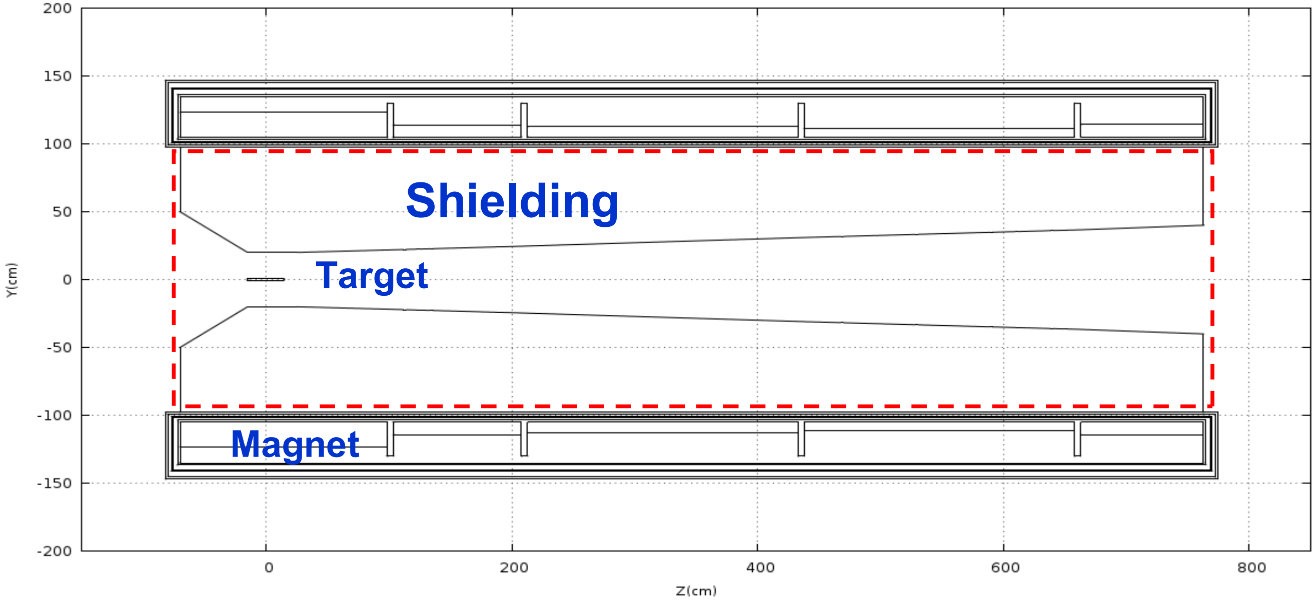
1. Introduction

Proton



Function of Shielding:

1. Protect equipments from high radiation
2. Absorb most of heat load from beam power
3. Minimize the heat load on magnets



Proton beam power =15 MW

Material: Tungsten

Length=8.33 m

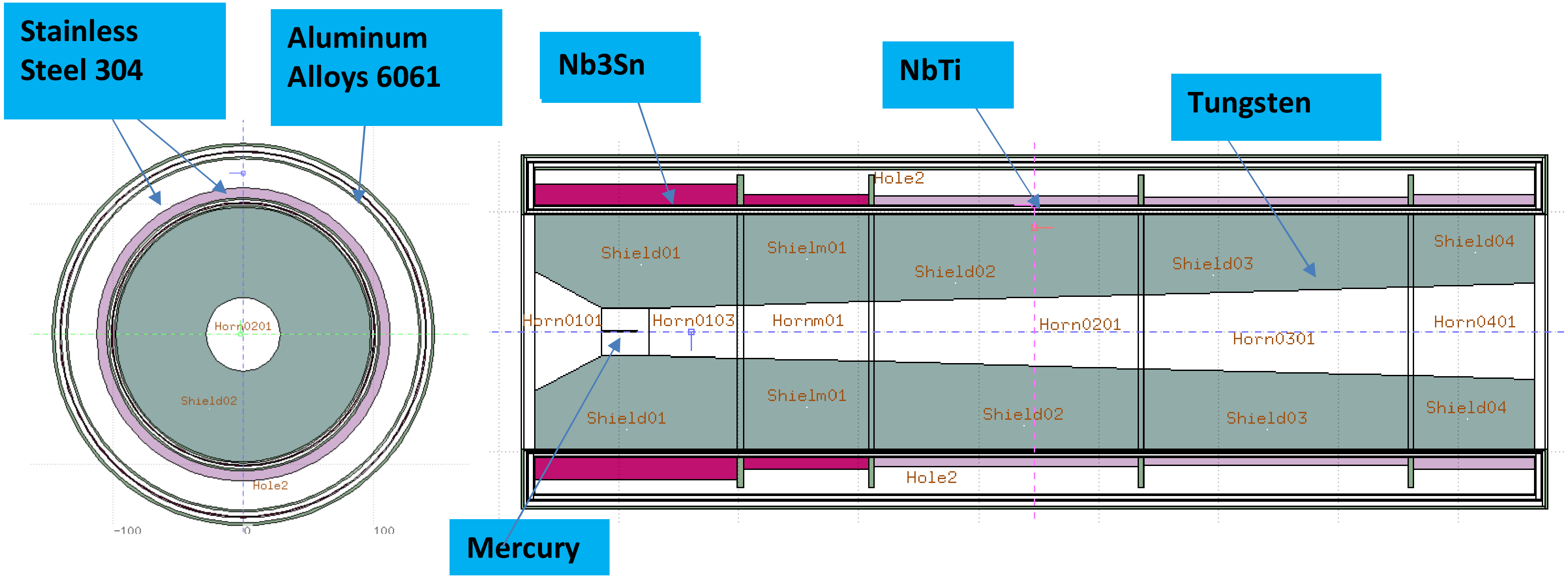
Diameter=2 m

Density=19 g/cc

Volume=22.5 m^3

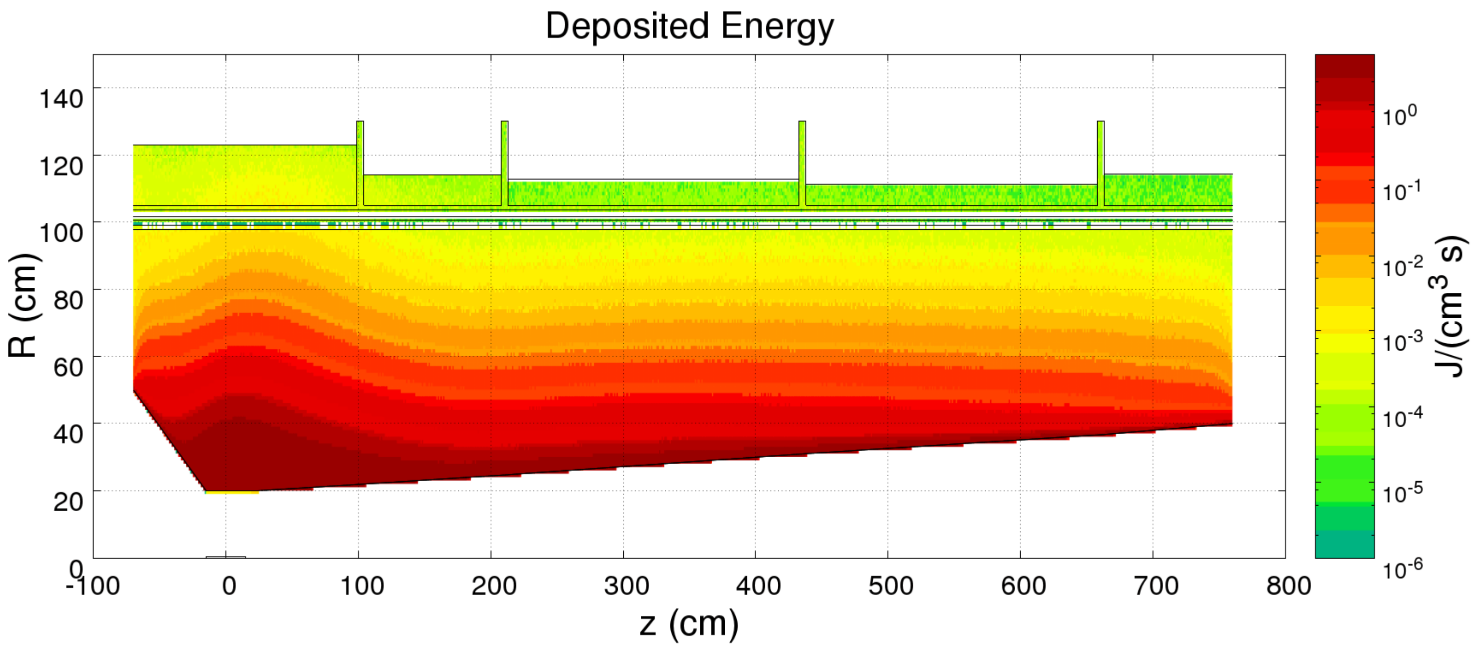
Mass=428 t

2.1 Heat deposition: Calculation Model of Fluka



Stainless steel 304: Fe 0.6775, Si 0.01, Mn 0.02, Cr 0.19, Ni 0.0925, N 0.01.
Aluminum Alloys 6061:Al 0.9725, Si 0.006, cu 0.002, Mg 0.01, Zn 0.0025, Mn 0.0015, Ti 0.0015, Cr 0.002, Fe 0.0035.
Nb3Sn: Nb 0.482, Cu 0.518.
NbTi conductor: polyimide 0.079(polyimide C6H11ON,Density1.41g/cc), Al 0.731, Cu 0.09, NbTi 0.1
Mecury: Density 13.534 g/cc
Tungsten: Density 19.3 g/cc

2.2 Heat deposition: Results



Heat deposition for Proton beam power = 15 MW

Proton: 1.5 GeV, 10 mA

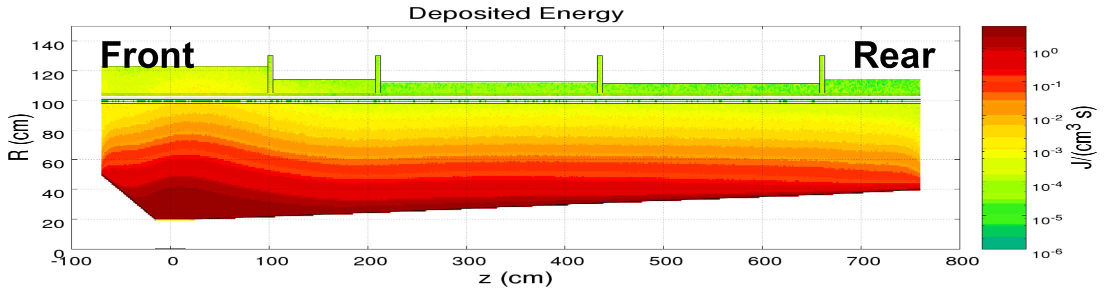
Target：Hg Length=300 mm, R=5 mm

Shielding: Tungsten

Heat load on Shielding: 9.9 MW
Max volumetric heat source=2.2x10^8[W m^-3]

3.1 Cooling Structure Design Criterion

1. For the shielding material density should be as high as possible, which reduce the heat load on superconducting magnets, the total volume of cooling channel can reduce the density of shielding and should be as small as possible;
2. It's not a good choice of cooling channel face to magnet, or along the radius direction, for the particle jet effect; The coolant passing through the shielding from front to rear also can prevent the irradiation damage on magnets;
3. Multiple rows of Mini-Channel with reasonable size can increase the heat transfer area and prevent decreasing the density too much. For the possessing difficulty of the tungsten, the channel should be as simple as possible;
4. For the high volumetric heat in shielding, the cooling channel should be designed to keep the shielding in demand especially near the target.



3.2 Coolant choice

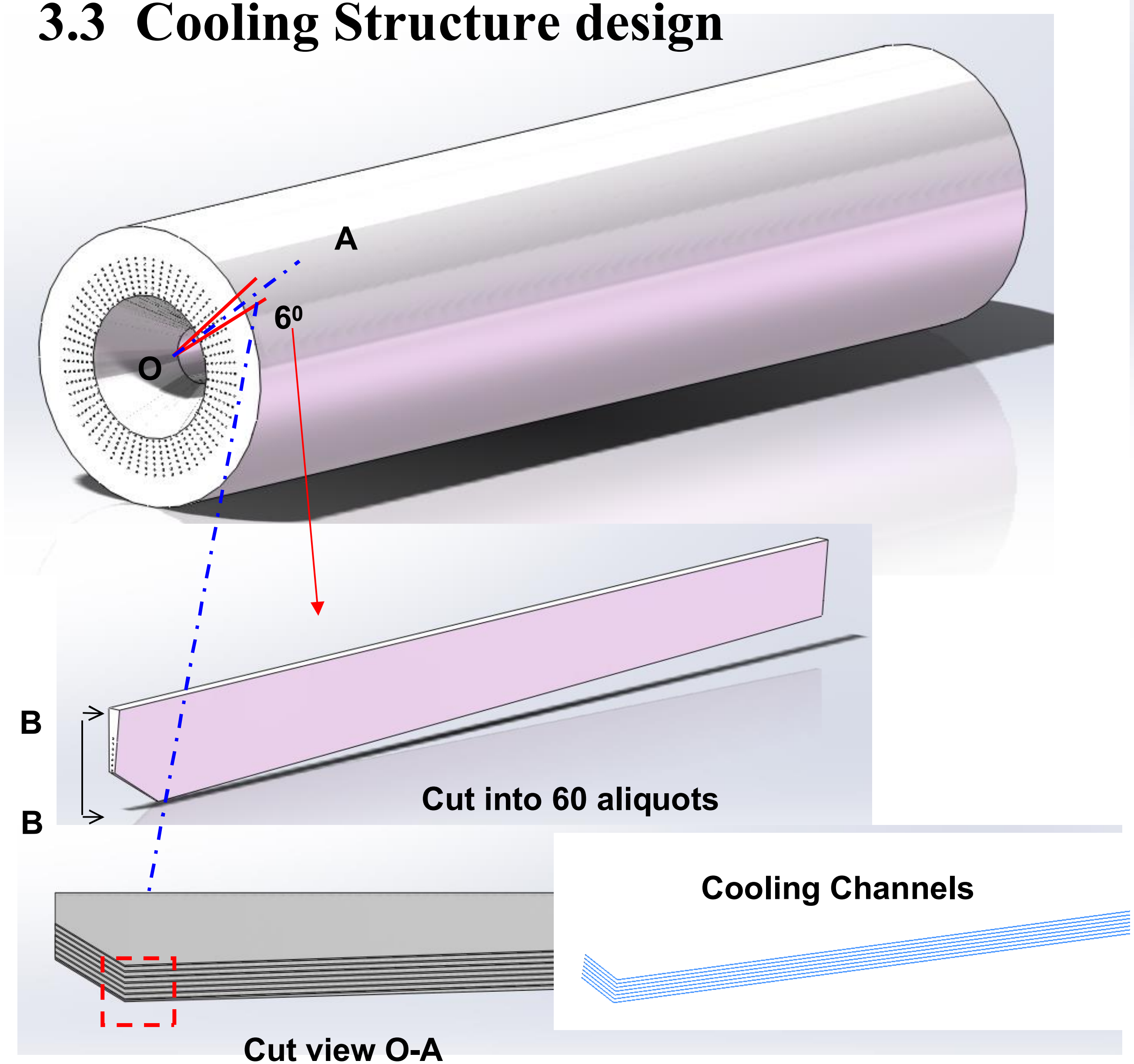
1. Water : good choice, inexpensive, high thermal conductivity, high material density, tungsten has to be cladded by tantalum
2. Helium : alternative choice, expensive, no new nuclide, tungsten no need cladded by tantanlum
3. Liquid metal (difficulty to deal with new generation of nuclides)

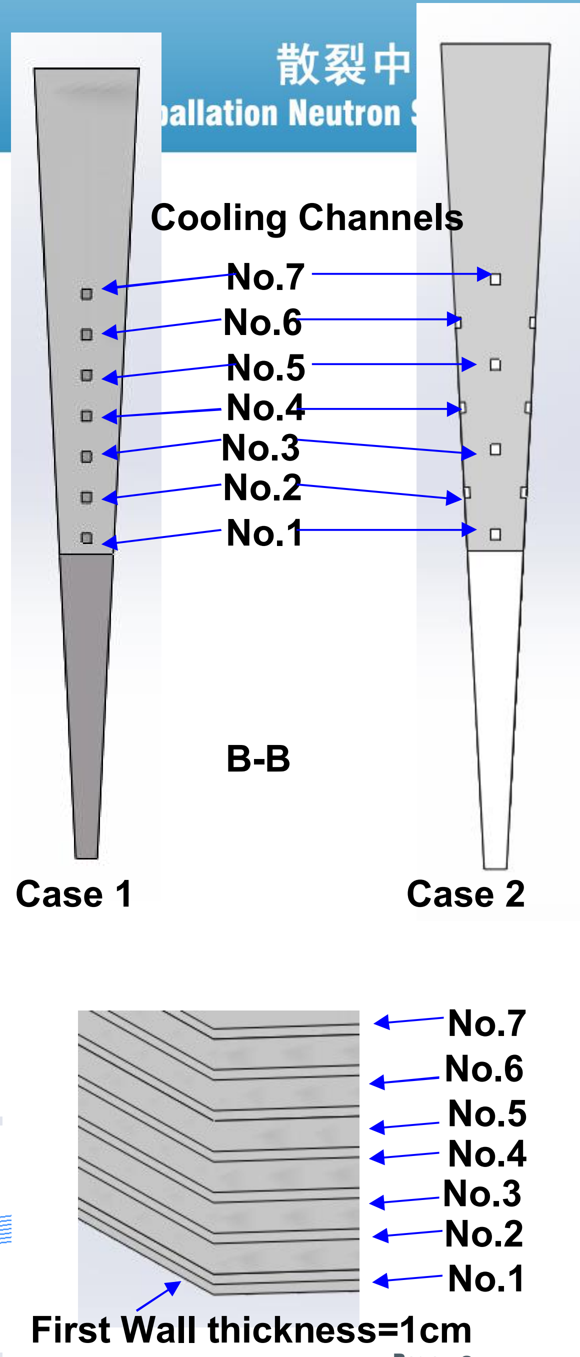
	Heat Condutivity (W /m-K)	Special Heat Capacity (J/kg-K)	Visousity (Pa/s)	Density (kg/m^3)
Water	0.6069	4181.7	8.899e-4	997
Helium@1atm 300K	0.1415	5240	1.86e-05	0.179
Helium@3Mpa 300K	0.158	5191	2.01e-05	4.78

Water: Max velocity 5 m/s； Goal: max temperature of water below 150 ℃ (keep in liquid phase), max temperature of tungsten below 800℃

Helium : Max velocity 100 m/s； Goal: max temperature below 800℃

3.3 Cooling Structure design





3.4 Government Equation & Calculation Software

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho U) = 0$$

$$\frac{\partial \rho U}{\partial t} + \nabla \bullet (\rho U \otimes U) - \nabla \bullet (\mu_{eff} \nabla U) = -\nabla P + \nabla \bullet (\mu_{eff} \nabla U)^T$$

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial p}{\partial t} + \nabla \bullet (\rho U h_{tot}) = \nabla \bullet (\lambda \nabla T) + \boxed{S_E}$$

$$\frac{\partial \rho k}{\partial t} + \nabla \bullet (\rho U k) = P_k - \beta^* \rho \omega k + \nabla \bullet [(\mu + \mu_t / \sigma_k) \nabla k]$$

$$\frac{\partial \rho \omega}{\partial t} + \bar{u}_j \frac{\partial \rho \omega}{\partial x_j} = \alpha_1 \frac{\omega}{k} P_k - \rho \beta \omega^2 + 2(1 - F_1) \rho \frac{\sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t / \sigma_w) \frac{\partial k}{\partial x_j} \right]$$

$$F_1 = \tanh \left\{ \min \left[\max \left(2 \frac{\sqrt{k}}{0.99 \omega y}, \frac{500 \mu}{y^2 \omega} \right), \frac{4 \sigma_{\omega 2} k}{CD_{k\omega} y^2} \right] \right\}^2$$

$$\nu_t = \frac{\alpha_1 k}{\max(a_1 \omega, \Omega F_2)} \qquad F_2 = \tanh \left[\max \left(2 \frac{\sqrt{k}}{0.99 \omega y}, \frac{500 \mu}{y^2 \omega} \right) \right]^2$$

$$P_k = \mu_t S^2 \quad S = \sqrt{2 S_{ij} S_{ij}} \quad S_{ij} = \frac{1}{2} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \quad \Omega = \sqrt{2 \Omega_{ij} \Omega_{ij}} \quad \Omega_{ij} = \frac{1}{2} \left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i} \right)$$

$$\beta^* = 0.09 \quad \alpha = 5/9, \beta = 3/40 \quad \sigma_k = \sigma_w = 2 \quad \sigma_{k2} = 1 \quad \sigma_{\omega 2} = 0.856 \quad \beta_2 = 0.0828$$

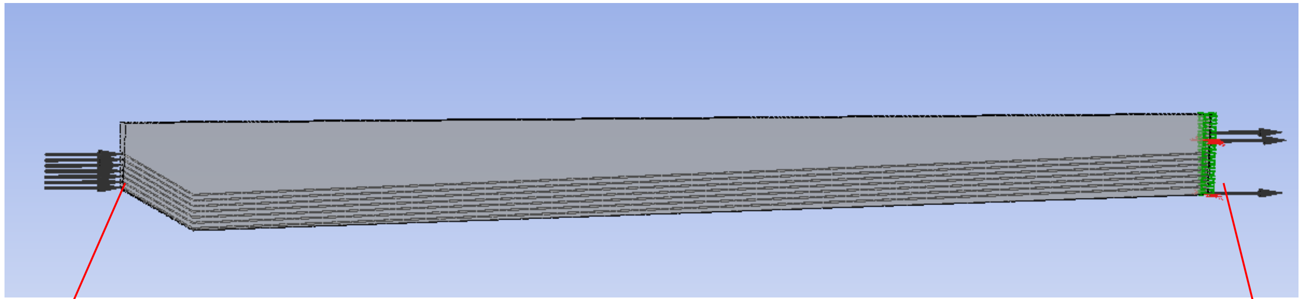
Wall: $k = 0 \quad \omega = 10 \dfrac{6\nu}{\beta y_1^2}$

Finite Volume Method

Software: Ansys CFX

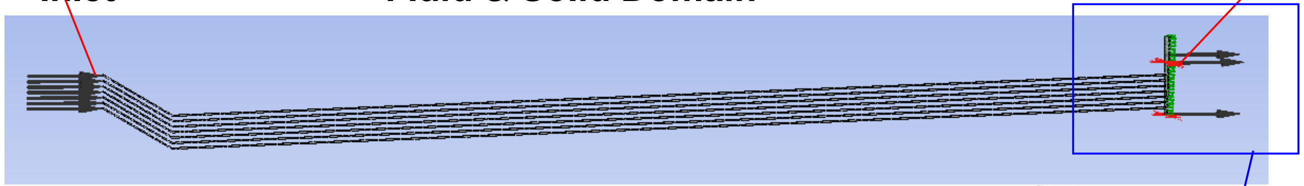
S_E **heat source**

3.5 Calculation Model in CFX

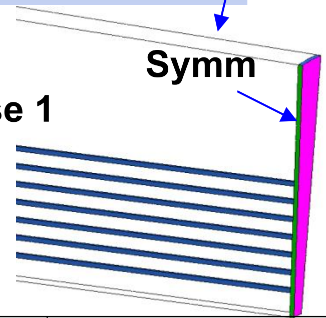


Inlet Velocity in channel
Water: 5 m/s
Helium: 50,75,100 m/s
Inlet Temperature 300 K
Outlet Pressure 0 Pa

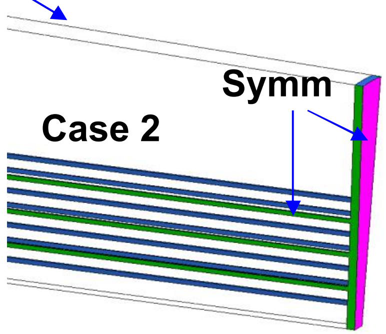
Inlet Fluid & Solid Domain Outlet



Fluid Domain



Case 1



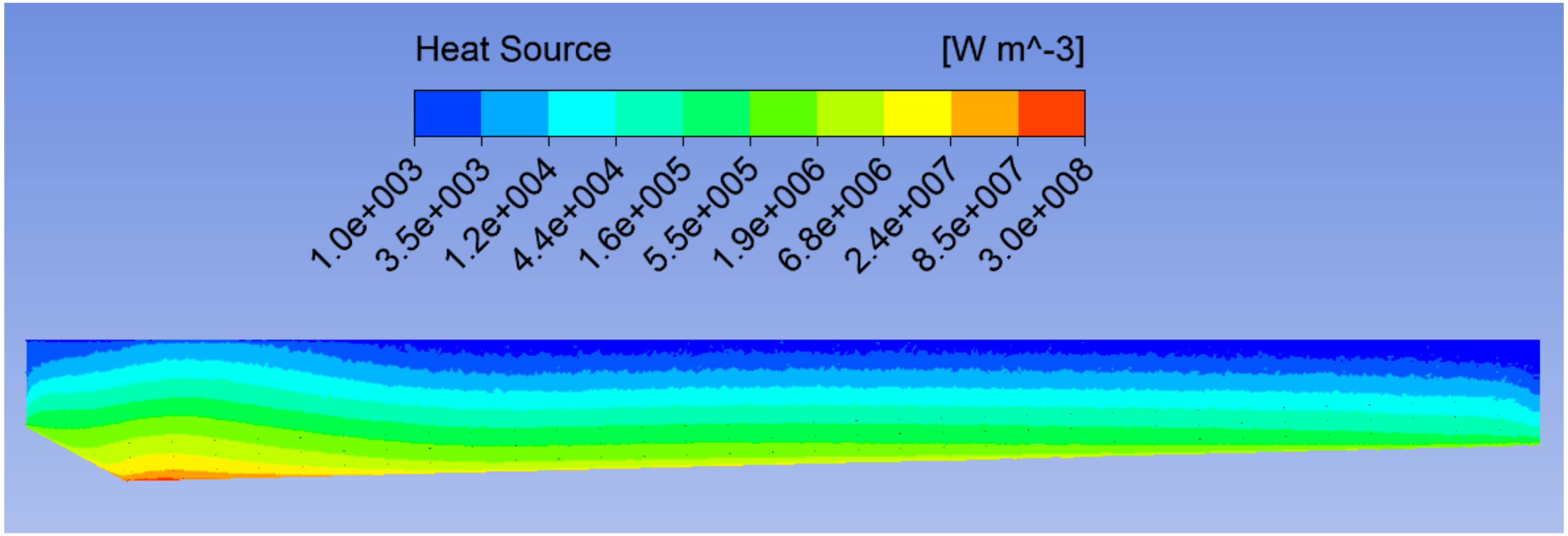
Case 2

Cooling Channels Size: 1cmX1cm
Volume of Cooling Channels: 0.00384648 m^3
Volume of Solid: 0.371984 m^3
Volume ratio of Cooling Channels = 1%

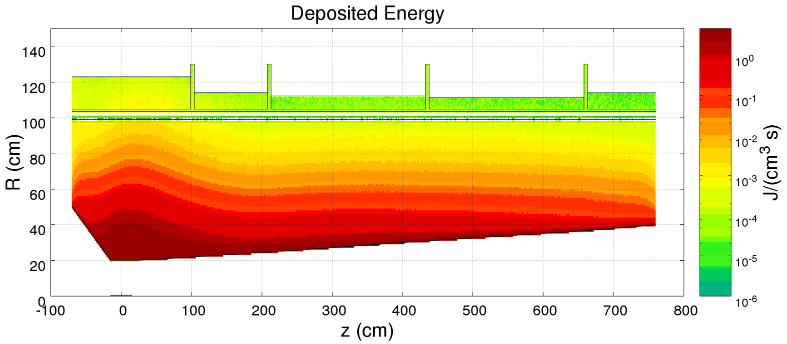
Properties of Tungsten and Water

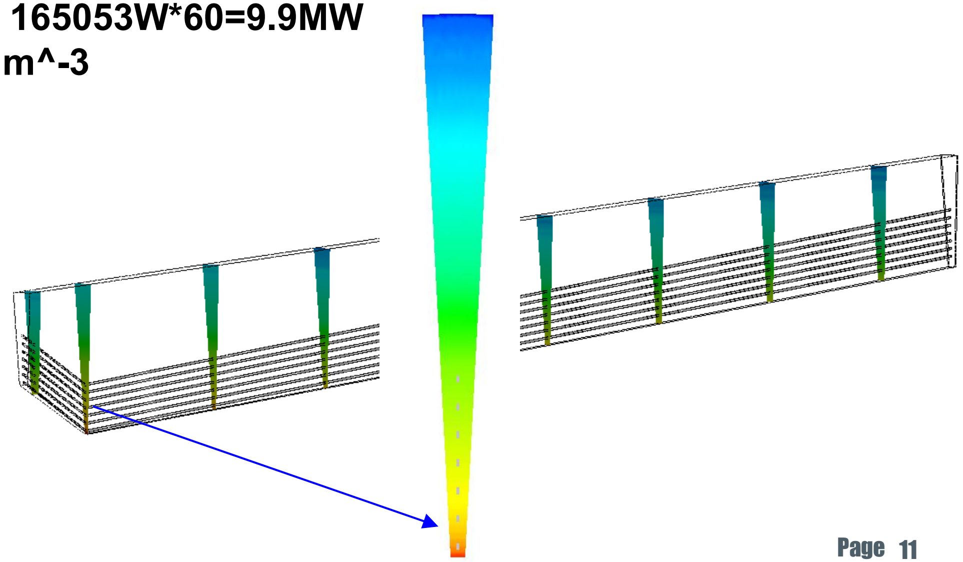
	Heat capacity (J/kg K)	Density (Kg/m^3)	Thermal Conductivity (W/m K)	Viscosity (Kg/m s)
Tungsten	134	19000	120	
Water	4181	997	0.6069	8.8×10^{-6}

3.6 Heat source in CFX

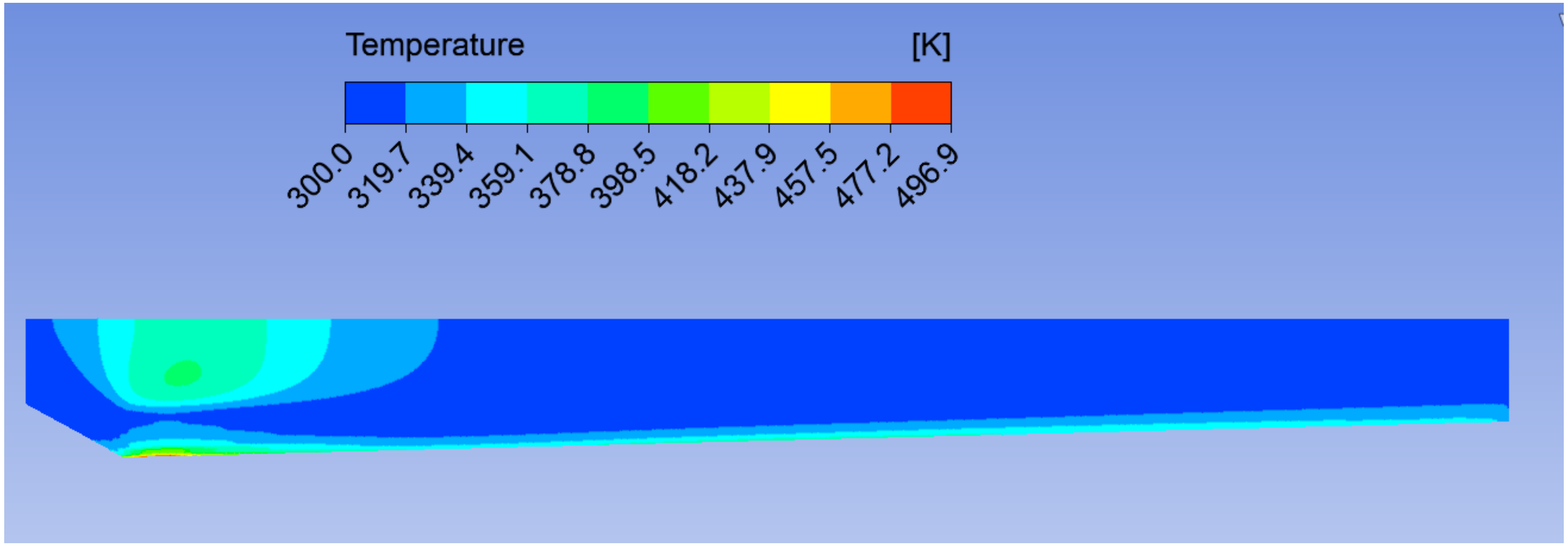


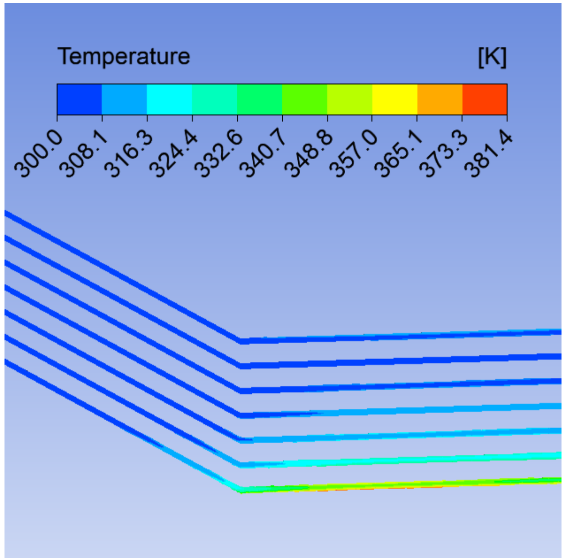
Heat load of shielding @Beam Power= 165053W*60=9.9MW
Max volumetric heat source=2.2x10^8 W m^-3





3.7 Results: case 1, water, 5 m/s





Pressure Drop= 0.8 MPa

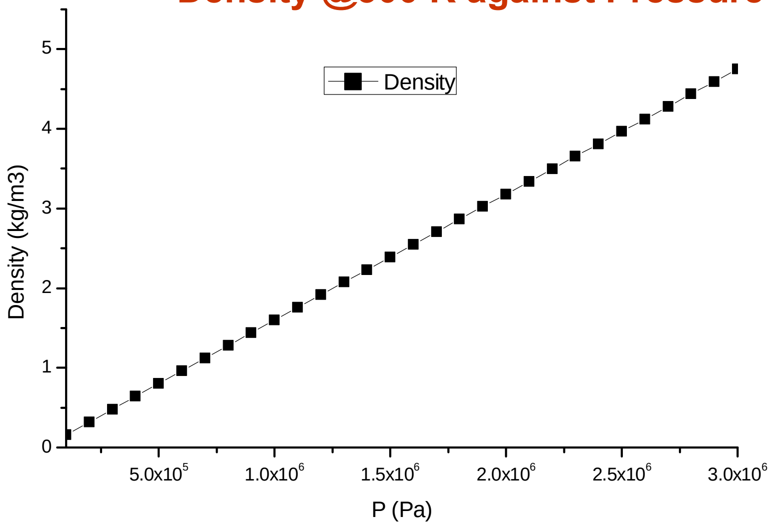
Outlet T=311.7 K ∆T=11.7 K

Mass flow rate=7X997 kg/m^3*5 m/s*0.0001 cm^2=3.49kg/s

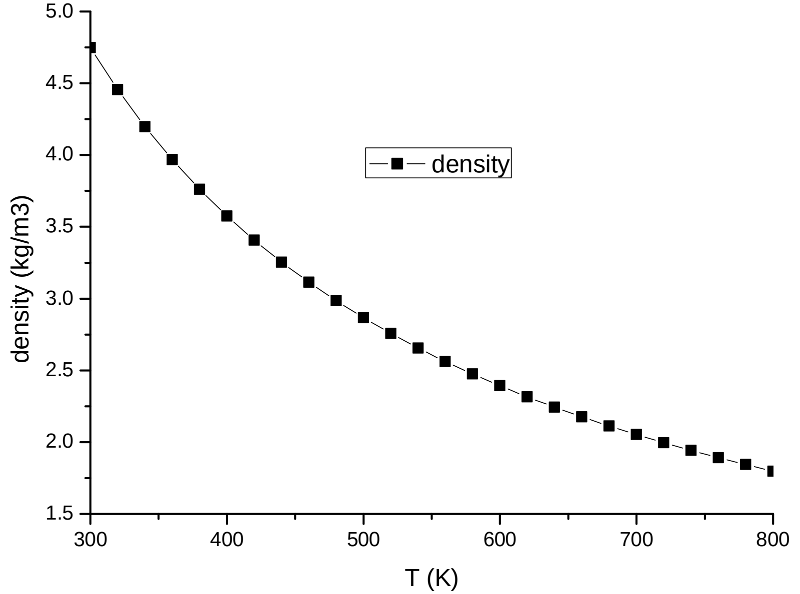
Total mass flow rate @ Shielding=206kg/s=744 m^3/h

3.8 Properties of Helium

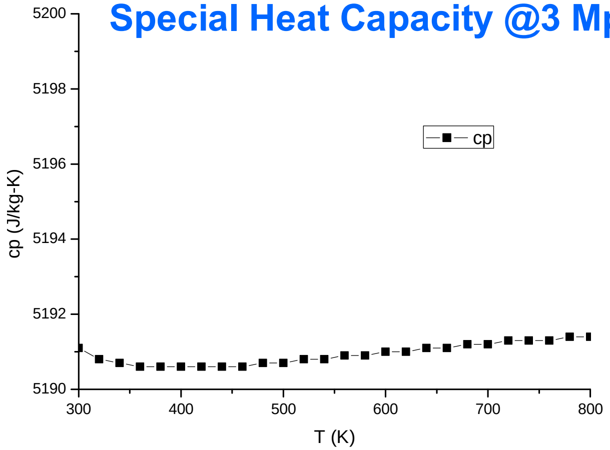
Density @300 K against Pressure



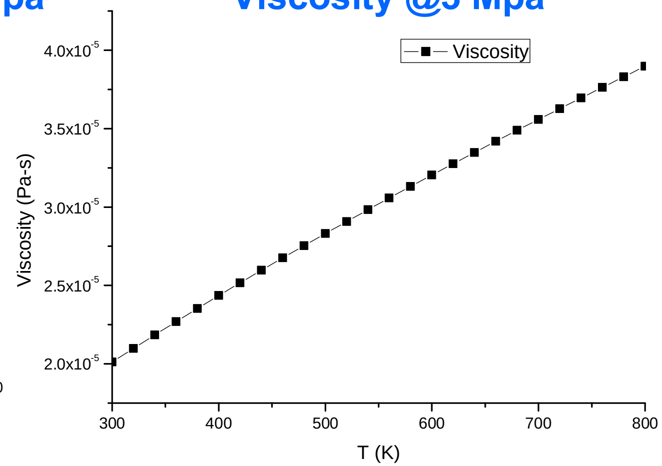
Density @3 Mpa against Temperature



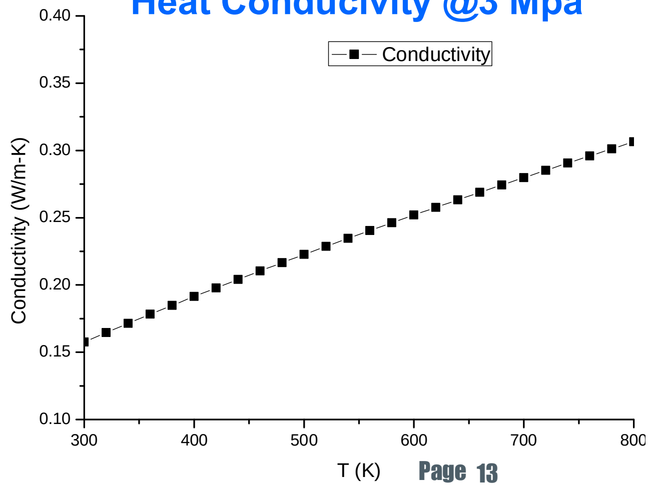
Special Heat Capacity @3 Mpa



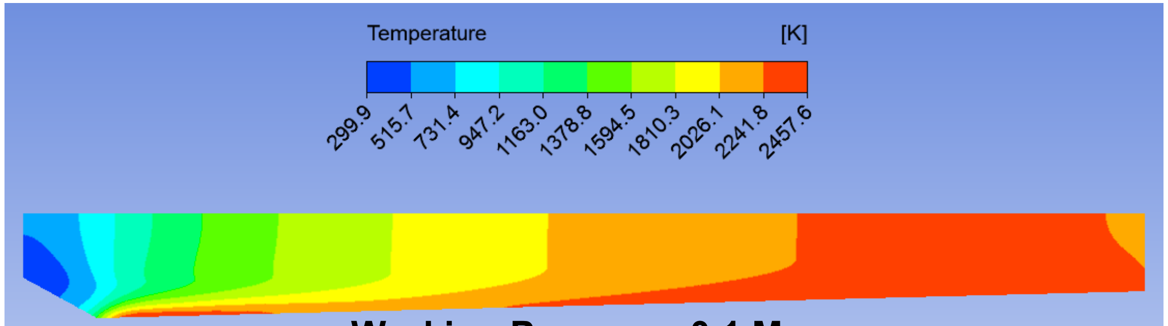
Viscosity @3 Mpa



Heat Conducivity @3 Mpa

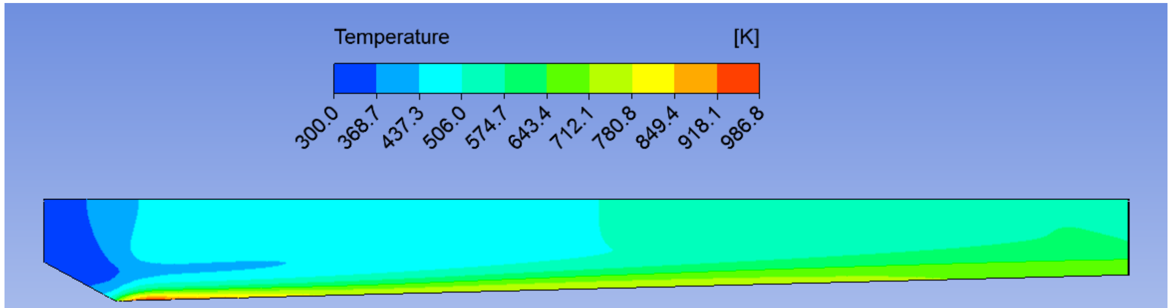


3.9 Comparison of Pressure: case 1, Helium, 100 m/s



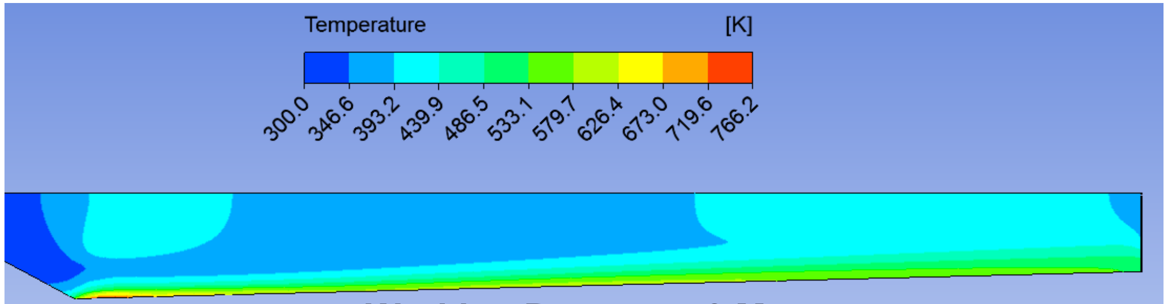
Working Pressure=0.1 Mpa

T@outlet=2204.2 K
T@outlet-T@inlet=1904.2 K
Max T=2184.5 ℃
Pressure drop=0.04 Mpa



Working Pressure=1 Mpa

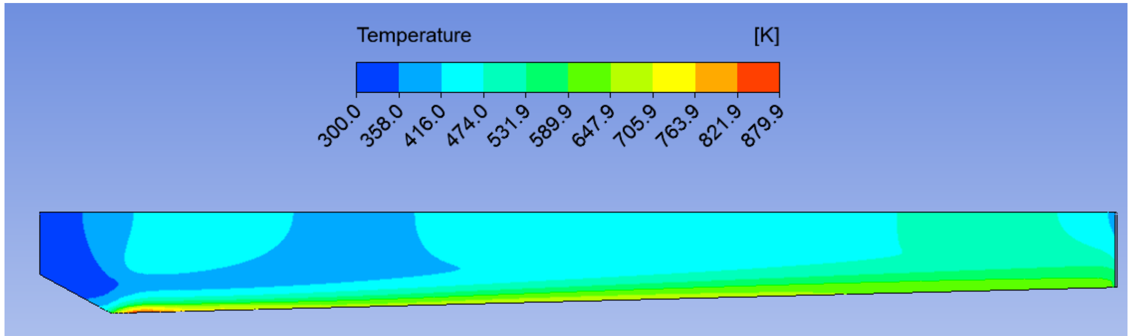
T@outlet=617.5 K
T@outlet-T@inlet=317.5 K
Max T=713.7 ℃
Pressure drop=0.48 Mpa



Working Pressure=2 Mpa

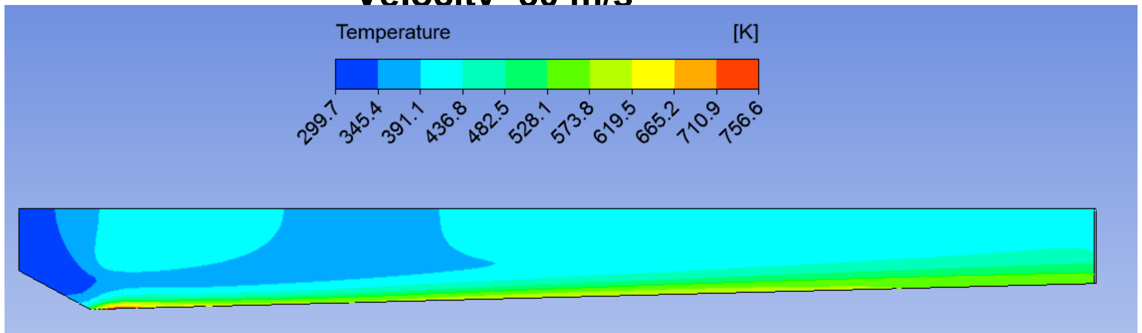
T@outlet=450.4 K
T@outlet-T@inlet=150.5 K
Max T=493.1 ℃
Pressure drop=0.83 Mpa

3.10 Comparison of veolicity: case 1, Helium, 3Mpa



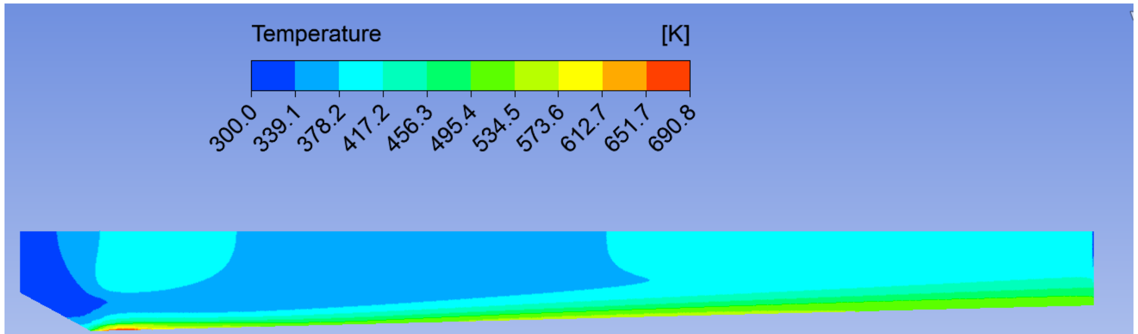
Velocity=50 m/s

T@outlet=519.3 K
T@outlet-T@inlet=219.3 K
Max T=603 ℃
Pressure drop=0.54Mpa



Velocity=75 m/s

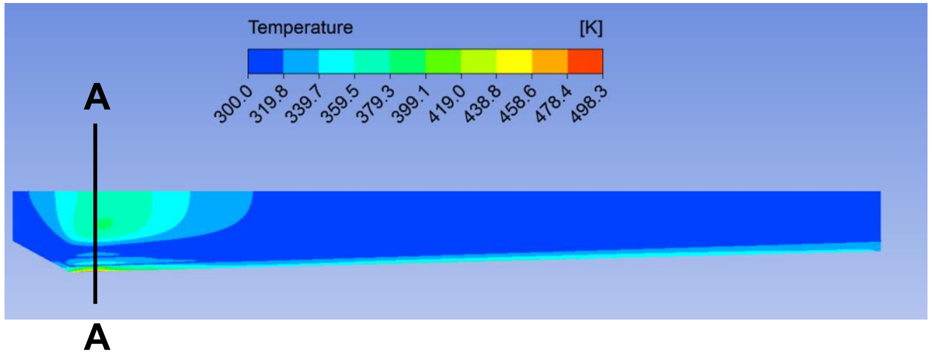
T@outlet=479.2 K
T@outlet-T@inlet=179.3 K
Max T=483 ℃
Pressure drop=1 Mpa

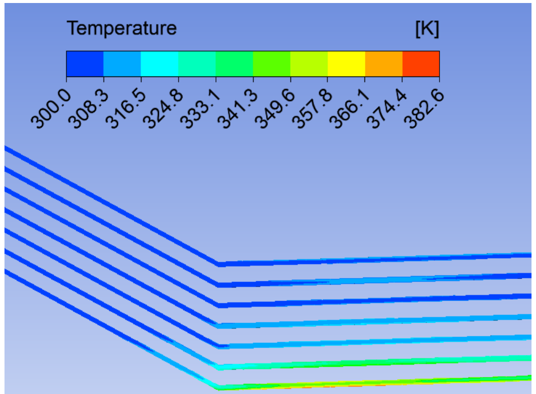


Velocity=100 m/s

T@outlet=428.4 K
T@outlet-T@inlet=128.4 K
Max T= 418 ℃
Pressure Drop=1.5 Mpa

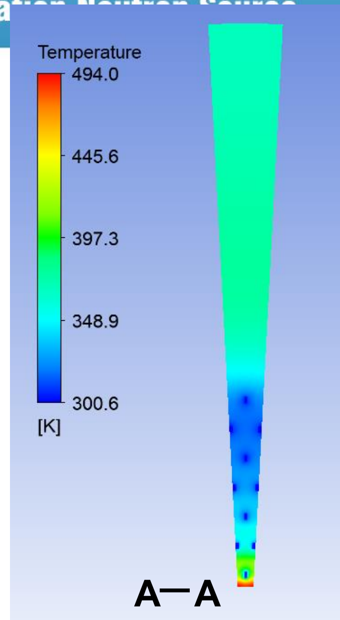
3.11 Comparion of Case 1 & Case 2： Water, 5 m/s



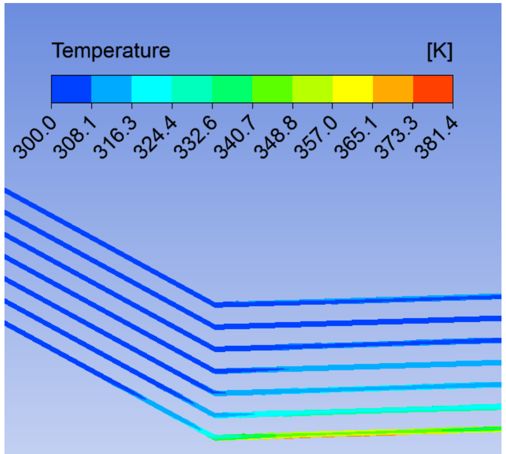


Fluid-solid Couping Surface

Case 2

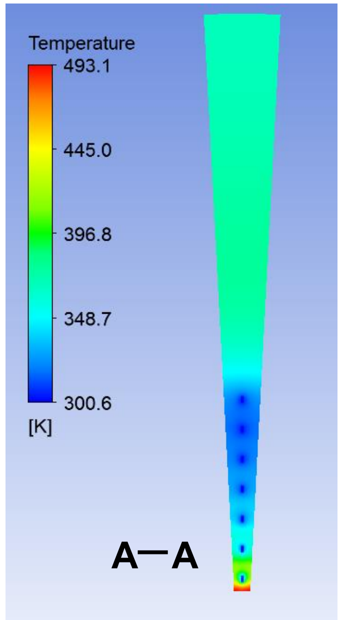


- For the high heat conductivity of water, the maximum temperature values of shielding and water in Case 1 and Case 2 are nearly same, but the temperature distribution is slightly different.
- The first wall thickness (position of No.1 channel) determines the maximum temperature, in this study, we use 1 cm.

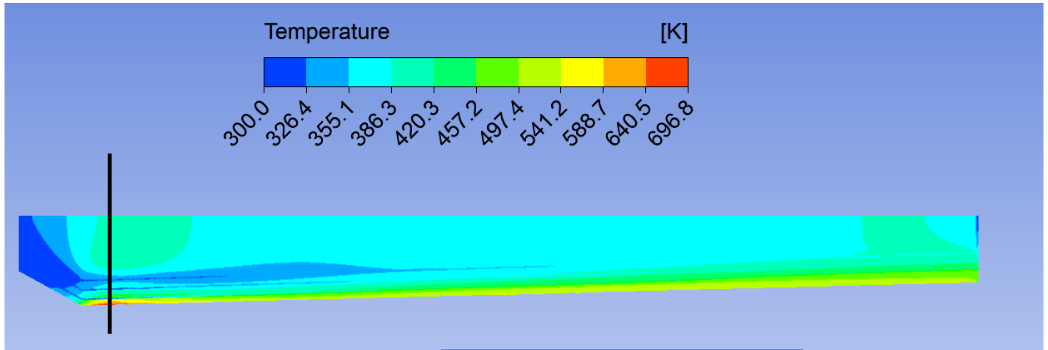


Fluid-solid Couping Surface

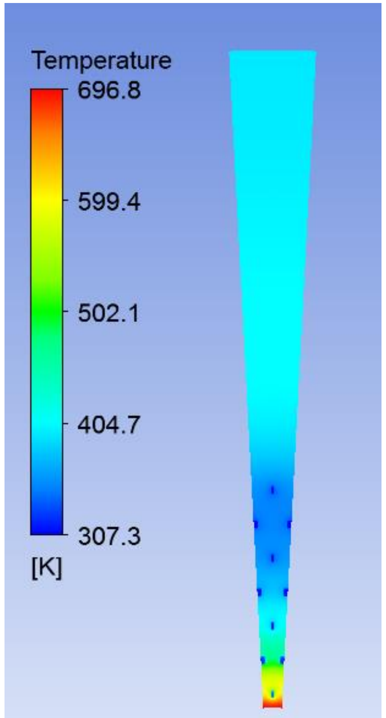
Case 1



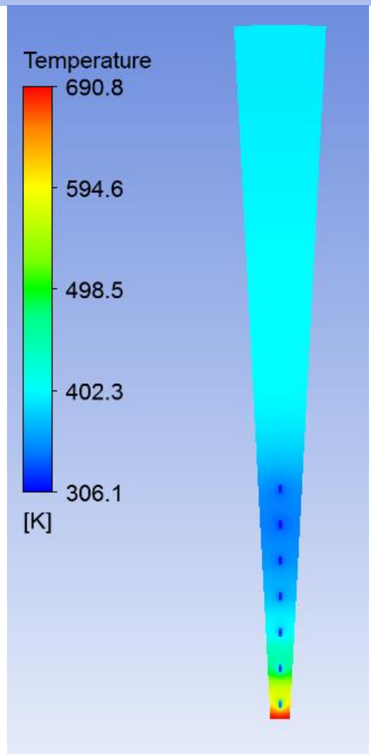
3.12 Comparion of Case 1 & Case 2: Helium, 100 m/s, 3 Mpa



Mass flow rate= 0.29879 [kg s^-1]
Total flow rate @Shielding=17.92 kg/s



Case 2



Case 1

The maximum temperature of shielding in Case 2 is higher than Case 1 at current conditions. The cooling channel distribution effect can not be ignored due to cold helium.

Conclusion

- From the Fluka calculation, the total heat load of shielding is about 10 MW and the maximum volumetric heat is above 100 W/cc , which is a challenge work for cooling design .
- Multiple Rows of Mini-Channel(MRMC), the shape of which is like a fold line to remove the highest volumetric heat, with reasonable channel size(1 cmX1 cm) and first wall thickness(1 cm), and the cooling direction of channel from front to rear, are premiliary ideals in the cooling structure design, and can minimize irradiation demage to magnets.
- For the corrosion in high temperature, tungsten should be cladded with tantalum, and the coolant water should be kept in single phase, the velocity should be very high.
- With MRMC and low first wall thickness, helium is a good coolant choice with high pressure and high velocity.
- Different channel distributions with constant first wall thickness has a different effects on the maximum temperature of shielding based due to the coolent thermal properities.
- It is possible to remove the high heat load and high volumetic heat on shielding at MOMENT using water or high pressure helium with MRMC.

Thank you for attentation